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Packet Radio Temporary Note No. 51

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Packet Radio Note: Preliminary Comparison of Different Access Modes

INTRODUCTION

Many access modes have been suggested for a packet radio net. Each has been analyzed in some way, to some degree. Although it seems much too early to make absolute or final judgements, it is possible to make some preliminary observations which may serve to help focus future analysis.

The purpose of this note is to make some preliminary comparisons of five possible access modes. Three of these, Aloha, Slotted Aloha, and Carrier Sense have been analyzed by others in several other TPRN's. Two new modes, Busy Tone, and Split Channel are analyzed. The Busy Tone mode is a natural extension of Carrier Sense, introduced to eliminate the "hidden-terminal" problem. (Not all terminals within the range of a single repeater will hear the carrier of all other terminals.) In this mode the repeater transmits an artificial carrier, or "busy tone" whenever the channel is busy. This tone is used by all terminals as if it were a carrier in a "carrier-sense" system. The Split Channel mode is a form of Reservation Aloha. A channel is set aside for use as a reservation channel, operated in the Aloha mode. A terminal (say terminal A) with a ready packet transmits its address (A) on the reservation channel. The repeater queues the terminals; when terminal A's turn comes, the repeater sends the terminal address (A) on the acknowledge channel or simply on the repeater-to-terminal message channel. This acts as both a transmit signal and acknowledgement to terminal A. These latter modes are described and partially analyzed in this note. We have included a brief analysis of the Carrier-Sense mode since our model differs slightly from previous models, and since this analysis helps in understanding the busy-tone analysis. The results for carrier sense are essentially identical to previous results.

GROUND RULES

We have compared the access modes by analysis of a repeater-terminal link. A network analysis may change the absolute results, but probably not the relative results. In all cases we assume a very large population of unperturbable users generating traffic with Poisson start times. For simplicity of comparison we assume:

(1) Terminals are within a 10-mile radius of the repeater. Maximum propagation delay from repeater to terminal is 54 μs.

(2) Bit rate = 100 kbs. Bit duration = 10^{-5} sec.

(3) Message packet size = 1000 bits.
Packet duration = 10 ms.

(4) In carrier sense, assume

Detection time = propagation delay = 54 μs.

(5) In busy tone, assume

Propagation delay time = 54 μs
SNR in busy tone = 30 dB
SNR in message channel = 10 dB

Detection time is inversely proportional to busy tone bandwidth.

(6) In split-channel, a total of 10,000 users is assumed. If each has a unique ID number, need 14 bits to represent the ID.

(7) Differential binary phase shift keying.

COMPARISON RESULTS

The results of this analysis are shown in Table I. The throughput is the ratio of bits/sec successfully transmitted to channel bit-rate. Although this is a reasonable measure for systems using a telephone channel, or a satellite channel where costs are determined by the bit-

	Aloha	Slotted Aloha	Carrier Sense	Busy Tone	Split-Channel
Maximum through-put	0.184	0.347	0.83	0.90	1.0
BW (Hz)	200 K	200 K	200 K	201 K	214 K
Efficiency (bit/Hz)	0.092	0.184	0.415	0.446	0.467
Efficiency ratio	1	2	4.5	4.8	5.1
Terminal receiver complexity	low	medium	medium	medium	medium
Repeater complexity	low	medium	low	medium	high
No. of channels available in 10 MHz, assuming 100% guard-band	25	25	25	24	23
Efficiency in 10 MHz BW Bit/Hz	0.046	0.092	0.207	0.223	0.233

Table I

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rate of the channel, throughput is not a complete indication in radio systems, where the limited resource is bandwidth. A better measure is the efficiency (in bits per Hz) of channel utilization. This measure follows throughput very closely for the modes shown; however, it will deviate markedly when we consider amplitude or time-capture effects (another note alas).

Also shown are the number of 200 kHz message channels which can be placed in a 10 MHz channel (assuming 100% guard-bands) and the efficiency of such a channel. This is for later comparison to a spread-spectrum system. (Preview--Aloha beats spread spectrum by about a factor of 50 in single-channel and only slightly in multi-channel operation.)

We have attempted to estimate the relative complexity only to show that it must be considered, and that a hole exists here. We have not attempted any comparisons on the basis of delay, although this is vital.

An examination of Table I shows that Carrier Sense, Busy Tone, and Split Channel are distinctly superior to Aloha or Slotted Aloha. However, the Carrier Sense analysis is probably optimistic since it ignores the hidden-terminal problem. Although the Split Channel mode seems to require a moderately complex repeater it has several distinct advantages not apparent in Table I:

- Overhead due to acknowledgement has been accounted for in analysis.
- Distributed traffic control is easily implemented.
- Time-of-arrival terminal location is possible.
- Certain crypto key generator sync problems are avoided.

It is too early to draw conclusions, but we feel that a reservation system deserves more complete analysis.

I CARRIER SENSE

A. Protocol

(1) When ready to send message, sense channel.

(2) If busy, wait random time and repeat (1).

(3) If not busy, send.

B. Model (Assumptions)

(1) Carrier can be reliably sensed in T_d seconds.

(2) Propagation time from relay to first terminal ready is T_p seconds.

(3) Aggregate process of listen time is Poisson point process with parameter λ.

(4) Very large number of terminals.

C. Analysis

Let

T_w = average waiting time

T_b = average busy time

T_m = packet duration

T_d = detection time

T_p = one hop propagation time

P_c = probability of conflict

P_s = probability of success

P_b = probability of busy

$a = 2(T_p + T_d)/T_m$

$b = T_d/T_m$

$G = \lambda T_m$

The channel has two states:

Busy--one or more messages being transmitted

Waiting--not busy.

We have

$$P_b = \frac{T_b}{T_b + T_w} \quad . \tag{1}$$

A successful try occurs when the channel is not busy and there is no conflict. Therefore,

$$P_s = (1 - P_b)(1 - P_c) \quad . \tag{2}$$

A conflict will occur if another terminal starts at any time later than $T_p + T_d$ before the first terminal looks since the first terminal will not detect it. If the other terminal starts later than $T_p + T_d$ after the first, it will detect the first. Therefore, conflicts occur whenever two terminals start within $2(T_p + T_d)$ of each other. Thus

$$P_c = 1 - e^{-2(T_d + T_p)\lambda} \quad , \tag{3}$$

The average busy time is given by

$$T_b = T_m(1 - P_c) + (T_m + T_d + T_p)P_c$$

$$= T_m + (T_d + T_p)P_c$$

T_b is an approximation since conflict time is upper bounded by $(T_m + T_p + T_d)$. Rewriting T_b in terms of a, G, and S and using Equation (3), we obtained

$$T_b = T_m \left[1 + \frac{a}{2} - \frac{a}{2} e^{-aG}\right] \tag{4}$$

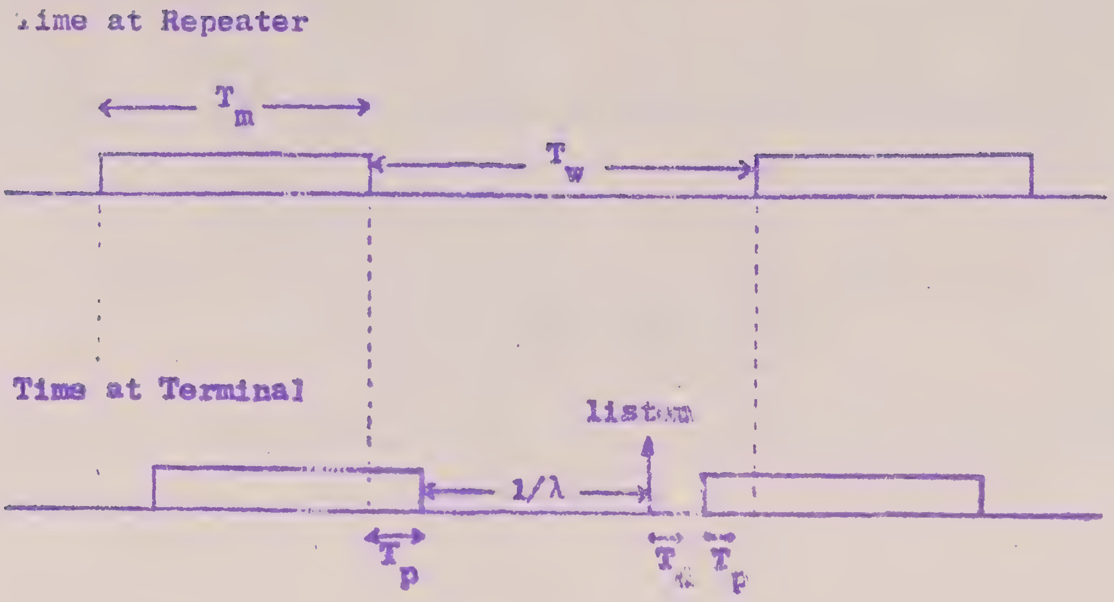

Figure 1

From Figure 1, we can see that the average waiting time as seen by the repeater is

$$T_w = \frac{1}{\lambda} + 2T_p + T_d$$

$$= T_m\left(\frac{1}{G} + a - b\right) \qquad (5)$$

Therefore, from Equation (1), the busy probability is

$$P_b = \frac{1 + \frac{a}{2} - \frac{a}{2}e^{-aG}}{1 + \frac{a}{2} - \frac{a}{2}e^{-aG} + \frac{1}{G} + a - b}$$

$$= \frac{1 + \frac{a}{2} - \frac{a}{2}e^{-aG}}{1 + \frac{3}{2}a - \frac{a}{2}e^{-aG} + \frac{1}{G} - b} \qquad (6)$$

Using Equations (2), (3), and (6), we obtain the throughput as

$$S = P_s G$$

$$= \frac{G(1 + aG - bG)e^{-aG}}{1 + G(1 + 1.5a - b - 0.5ae^{-aG})} \qquad (7)$$

Throughputs for the carrier sense system is plotted in Figure 2 for different values of a with $b = 5 \times 10^{-3}$.

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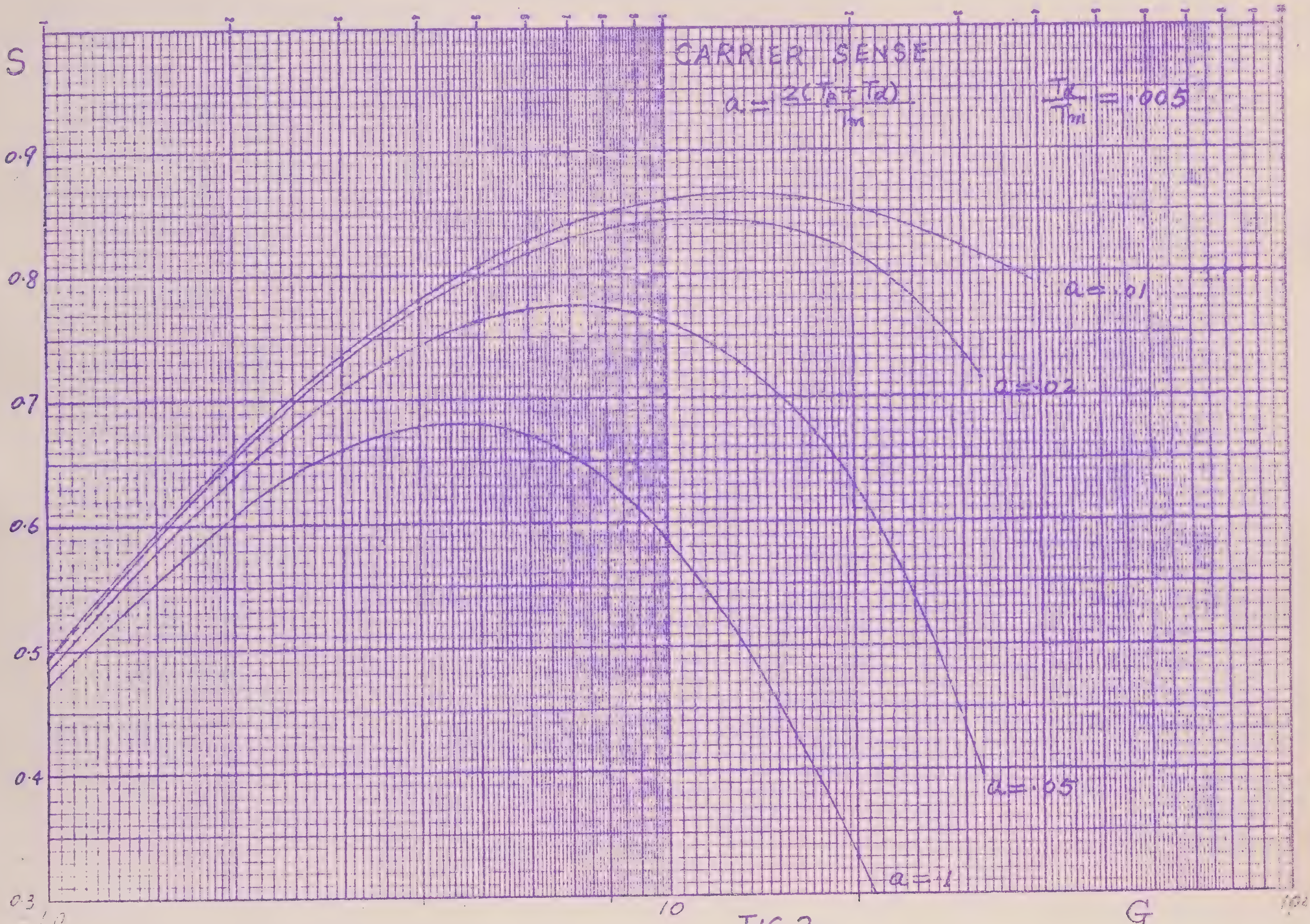

FIG 2

II BUSY TONE

A. Protocol

Two channels: A message channel

A busy-tone channel.

Terminal Sequence:

(1) When ready to send message, sense busy tone.

(2) If busy, recycle to (1) at random time.

(3) If not busy, send request burst on busy-tone channel.

(4) When responding busy tone is sensed, prepare to send message.

(5) When responding busy tone ends, send message.

Relay Sequence:

(1) When request burst is received, start responding busy tone.

(2) As soon as message channel is empty, stop response, except response must last long enough for detection.

B. Model

(1) Busy tone can be reliably detected in T_d seconds.

(2) All terminals at maximum range, i.e., propagation time T_p is constant.

(3) Aggregate process of "look" time is Poisson point process with parameter λ.

C. Analysis

Consider the timing sequence shown in Figure 3.

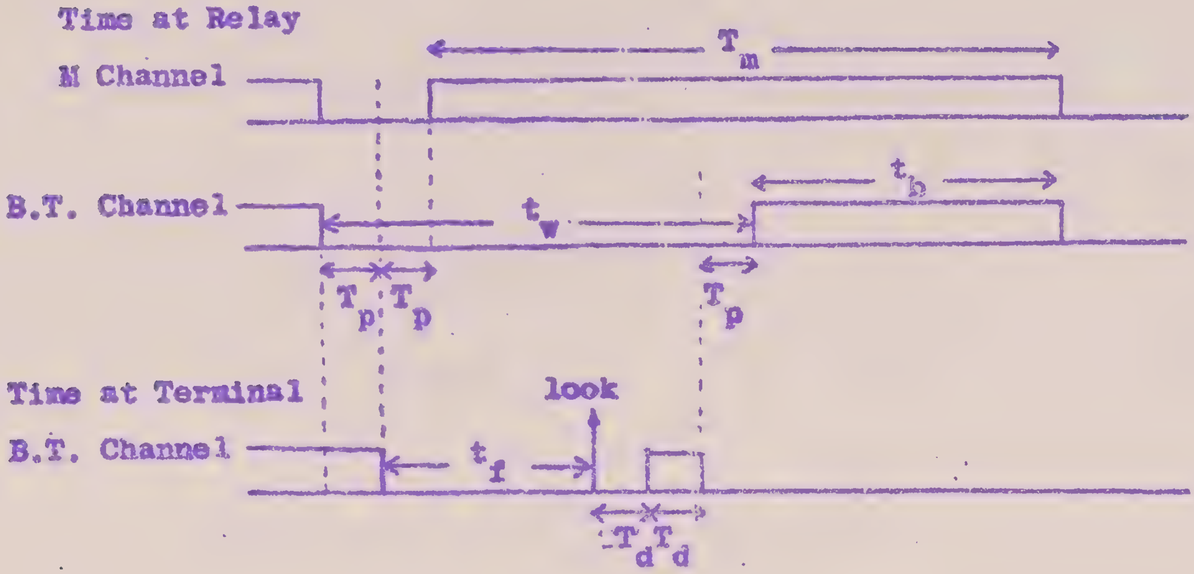

Figure 3

If t_w is the time as seen by the relay such that the Busy Tone channel is not busy, then

$$t_w = T_p + t_f + 2T_d + T_p \tag{1}$$

and the average of t_w is

$$T_w = 2(T_p + T_d) + 1/\lambda \tag{2}$$

The busy time t_b of the Busy Tone channel as seen by the relay is

$$t_b = \begin{cases} T_m + 2T_p - 2T_p - 2T_d - t_f & t_b \geq T_d \\ T_d & \text{otherwise} \end{cases} \tag{3}$$

where t_f is exponentially distributed with mean $1/\lambda$.

For $t_b \geq T_d$, from Equation (3) we obtain

$$T_m - 2T_d - t_f \geq T_d \quad ,$$

i.e.,

$$t_f \leq T_m - 3T_d$$
$$= L \tag{4}$$

So that the average busy time is

$$T_b = \int_0^\infty t\Pr(t_b = t)dt$$

$$= \int_0^L (T_m - 2T_d - t)\lambda e^{-\lambda t}dt + T_d\lambda \int_L^\infty e^{-\lambda t}dt$$

$$= T_m - 2T_d - (1 - e^{-\lambda L})/\lambda \tag{5}$$

The probability that the Busy Tone is on is approximately

$$P_b = \frac{T_b}{T_b + T_v} \tag{6}$$

A successful attempt to send a message will occur whenever the Busy Tone is off during a "look" and no conflict occur.

With probability of conflict

$$P_c \leq 1 - e^{-2\lambda(T_p + T_d)} \tag{7}$$

We obtain the throughput

$$S \geq G(1 - P_b)(1 - P_c)$$

$$= G\frac{T_w}{T_b + T_w}e^{-2\lambda(T_p + T_d)}$$

$$= \frac{G(1 + aG)e^{-aG}}{G(1 + a - 2b) + e^{-G + 3bG}} \tag{8}$$

where, as in carrier sense,

$$a = 2(T_p + T_d)/T_m$$

$$b = T_d/T_m$$

Equation (8) is plotted in Figure 4 with different values of a and with $b = 5 \times 10^{-3}$.

Although S is the throughput, it does not accurately measure the efficiency because the busy tone uses some bandwidth. The efficiency η can be defined as

$$\eta = \frac{W_m}{W_m + W_B} S \qquad (9)$$

where

W_m = message BW

W_B = busy tone BW

Assume that the same peak power is used for Busy Tone as for message and assume that message SNR for suitable operation is 10 and that we need a SNR of 10^3 for proper detection of busy tone. Then if the rise in the busy-tone detect filter is exponential, the amplitude at time T_d is

$$A_{BT} = A_M \left(1 - e^{-\frac{T_d}{k}}\right) \qquad (10)$$

where

A_{BT} = Amplitude of busy tone

A_M = Amplitude of message

k = time constant of W_B filter

For 10 dB SNR in message channel

$$A_M = \sqrt{20\, N_o W_m}$$

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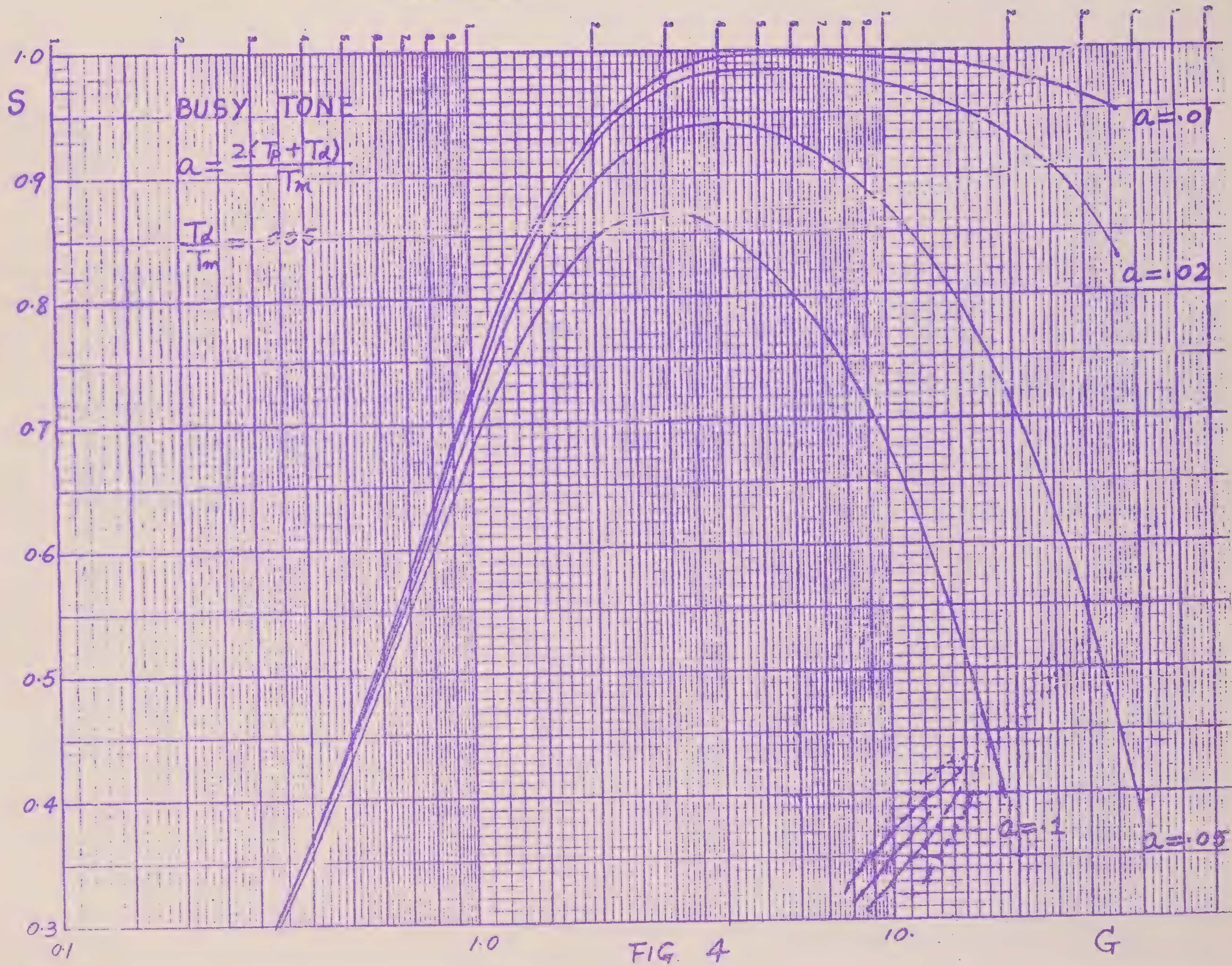

FIG. 4

For 30 dB in Busy Tone channel

$$A_{BT} = \sqrt{2 \times 10^3 N_o W_B}$$

Hence T_d may be found from

$$\sqrt{2 \times 10^3 N_o W_B} = \sqrt{20 N_o W_m} \quad (1 - e^{-\frac{T_d}{k}})$$

Assuming $k = \frac{1}{2W_B}$ and solving for T_d,

$$T_d = - \frac{1}{2W_B} \log_e (1 - 10\sqrt{\alpha}) \qquad (11)$$

where

$$\alpha = \frac{W_B}{W_m} \quad .$$

Substituting for T_d in S, assuming $N = T_m W_m$ and after some algebric manipulation, we arrive at

$$\eta = \frac{1}{1 + \alpha} \; \frac{G \left[1 - \frac{G}{\alpha N} \log_e (1 - 10\sqrt{\alpha}\,) + 2\beta G \right] e^{-2\beta G} (1 - 10\sqrt{\alpha}\,)^{\frac{G}{\alpha N}}}{G(1 + 2\beta) + e^{-G} (1 - 10\sqrt{\alpha})^{-\frac{3G}{2\alpha N}}} \qquad (12)$$

where

$$\beta = \frac{T_p}{T_m} \quad .$$

Equation (12) is plotted for

$T_p = 54\ \mu s$

$T_m = 10$ ms

$\beta = 5.4 \times 10^{-3}$

$W_m = 200$ kHz

$N = T_m W_m = 2 \times 10^3$

and different values of α. This is shown as Figure 5.

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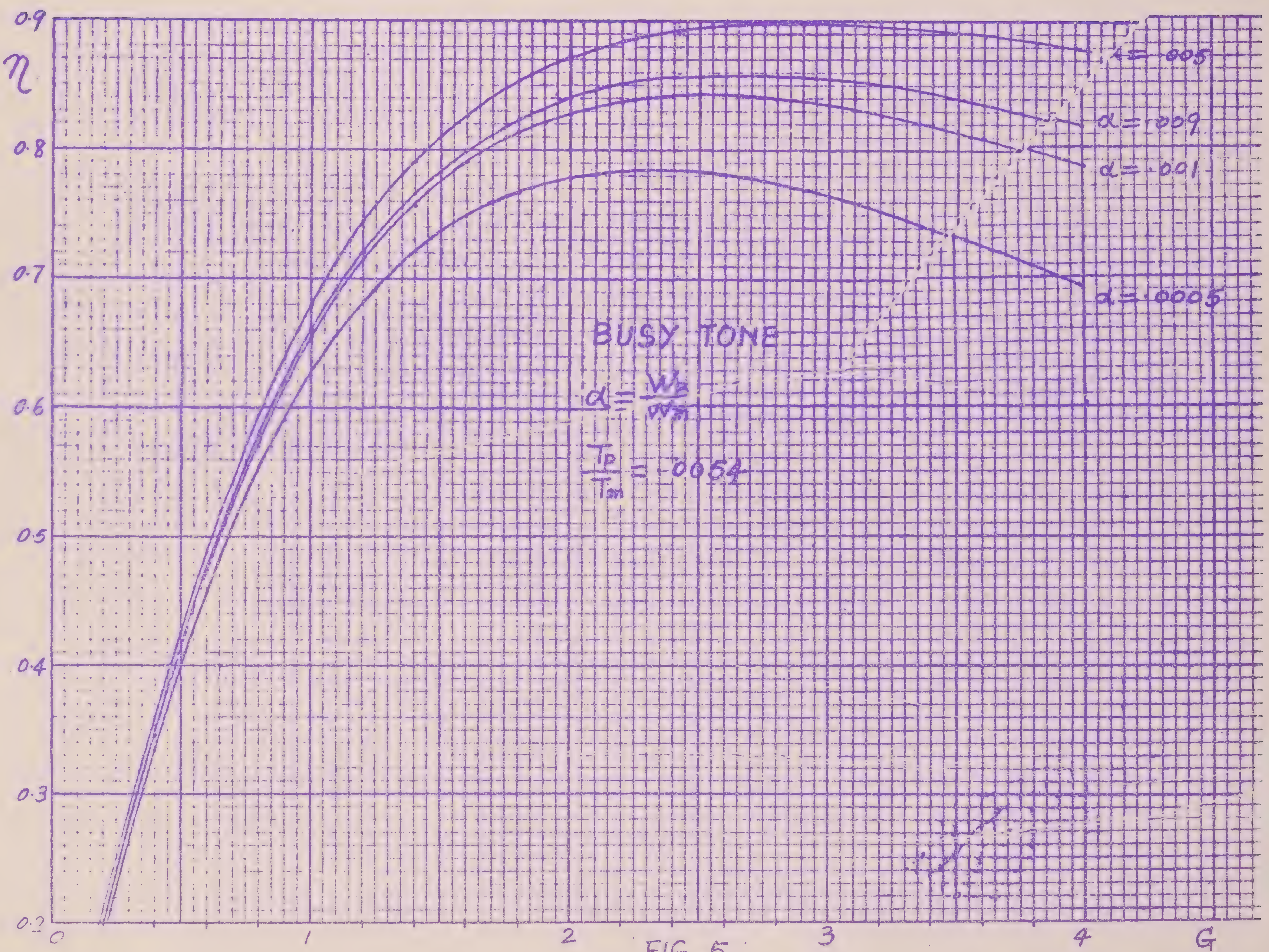

FIG 5

III SPLIT-CHANNEL

To increase the channel utilization above the Aloha mode, the concept of split-channel system is described here and a preliminary analysis is given in this note.

The communication net considered here consists of a relay station and a number of mobile terminals around it. Two one-way channels of certain bandwidth are available for two-way radio communication between the relay station and the terminals. If Aloha random access mode is used, the channel utilization or throughput for the terminal-to-relay channel is 1/2e. In this split-channel system, each one-way channel is split into two channels of unequal bandwidths, one for the request channel and the other message channel.

Both the request and message channel for the relay-to-terminal transmission are in broadcast mode, only the terminal-to-relay channels need be analyzed. For routing purposes, each terminal will have an

identity number (ID) to identify itself. The request channel will be operated in the Aloha random access mode. To initiate the sending of a message packet in the message channel, the terminal will send its own ID number by the request channel. This ID number, when received correctly by the relay station, will be sequenced with other previously received ID's. When the message channel is available to a particular terminal, that terminal ID is broadcasted through the relay-to-terminal request channel. After hearing its own ID repeated by the relay station, the terminal start transmitting its message in the message channel. If a terminal does not hear its own ID repeated by the relay after a certain time after the ID is sent, the original request transmission is assumed to be lost or in conflict with other requests. Request signal is sent again.

Analysis:

Let BW = bandwidth of terminal-to-relay channel.

BW_r = request channel bandwidth

BW_m = message channel bandwidth.

Then $BW = BW_r + BW_m$

Assuming bit rate in request channel $= \alpha BW_r = b_r$

Assuming bit rate in message channel $= \alpha BW_m = b_m$

where α is some constant.

Let n = number of bits in request signal

m = number of bits in message packet.

For realistic cases $\frac{n}{m} \ll 1$.

Request channel is in Aloha mode, therefore maximum throughput is $\frac{1}{2e}$.
Maximum number of successful request

$$= \frac{b_r}{2e}/n \quad \text{per sec.}$$

Given an average of k message packets per request, the total number of requested message packets per second

$$= \frac{b_r}{2en} \cdot k$$

Assuming message channel is filled

i.e.,
$$\frac{b_r}{2en} kT = 1 \qquad (1)$$

where T is the duration of one message packet.

$$T = \frac{m}{b_m} \qquad (2)$$

From (1) and (2)

$$\frac{b_r k}{2en} \cdot \frac{m}{b_m} = 1$$

i.e.,
$$\frac{b_r}{b_m} = \frac{2e}{k}\left(\frac{n}{m}\right) \qquad (3)$$

$$\text{Channel utilization} = \frac{b_m}{b_r + b_m}$$

$$= \frac{k}{2e\left(\frac{n}{m}\right) + k} \qquad (4)$$

also

$$\frac{BW_r}{BW} = \frac{1}{1 + \frac{k}{2e}\left(\frac{m}{n}\right)} \qquad (5)$$

Equation (4) and (5) are plotted in Figures 6 and 7.

This split-channel system is actually some kind of time division multiplex system, using the request channel for synchronization purposes.

Messages need not be sent in fixed length packets, the case for k = 1 corresponds to variable message length with mean value equals to m bits.

Advantages of the split-channel system:

1. Much higher channel utilization, utilization is greater than 0.94 for $\frac{n}{m} < 0.01$.
2. The repeated ID by the relay station corresponds to a positive acknowledgment in the request channel.
3. The request signal besides containing the terminal ID, may contain information of priority and length of message.
4. Once the relay station has the information of the number of terminals waiting to transmit messages and their message lengths, network status can be broadcast by the relay station to terminals from time to time to smooth traffic.
5. If the relay station is equipped with directional antennas and precision clock,the location of the mobile terminal can be estimated.

To estimate the direction of the mobile terminal, the following scheme may be used.

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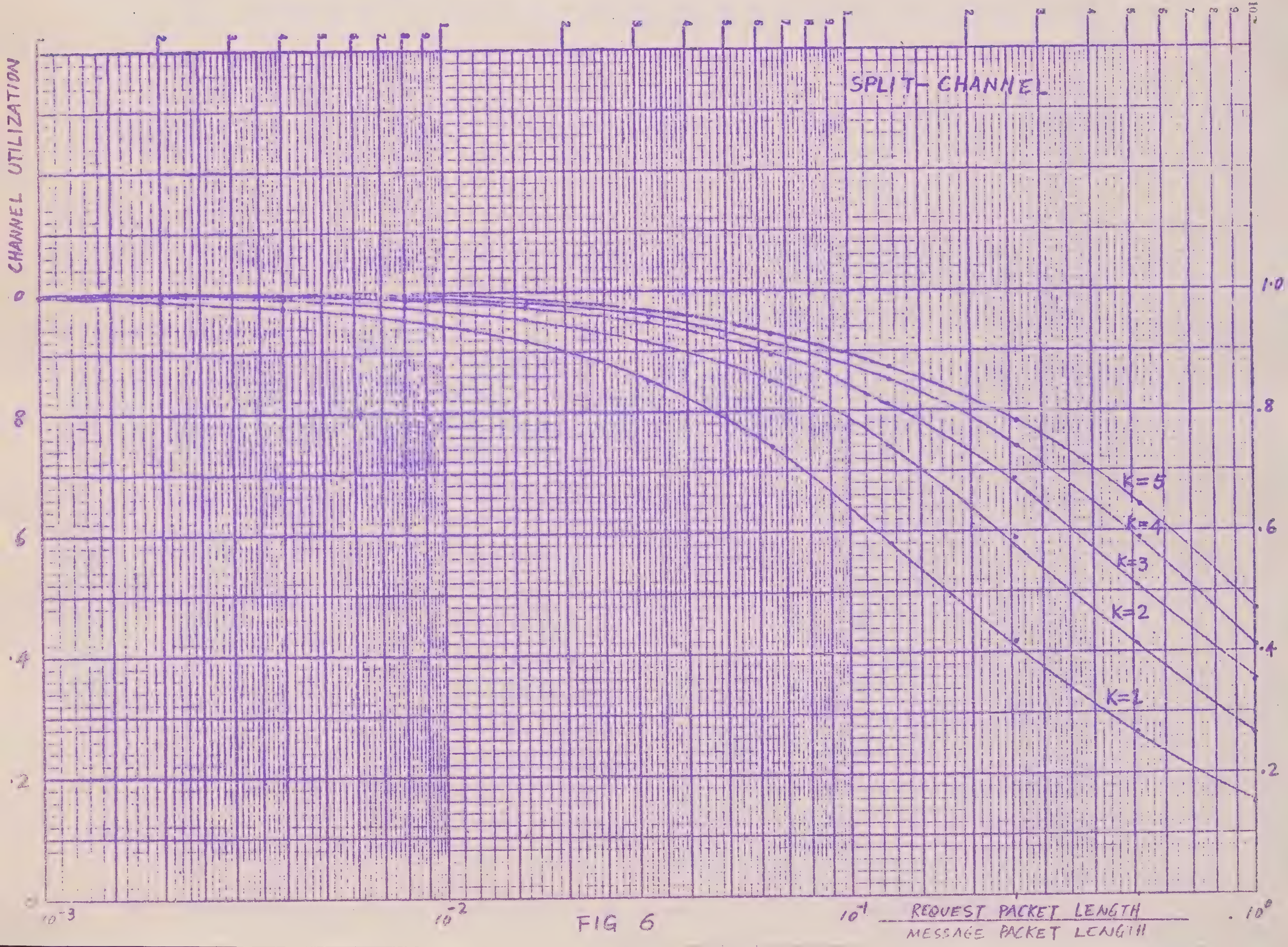


FIG 6

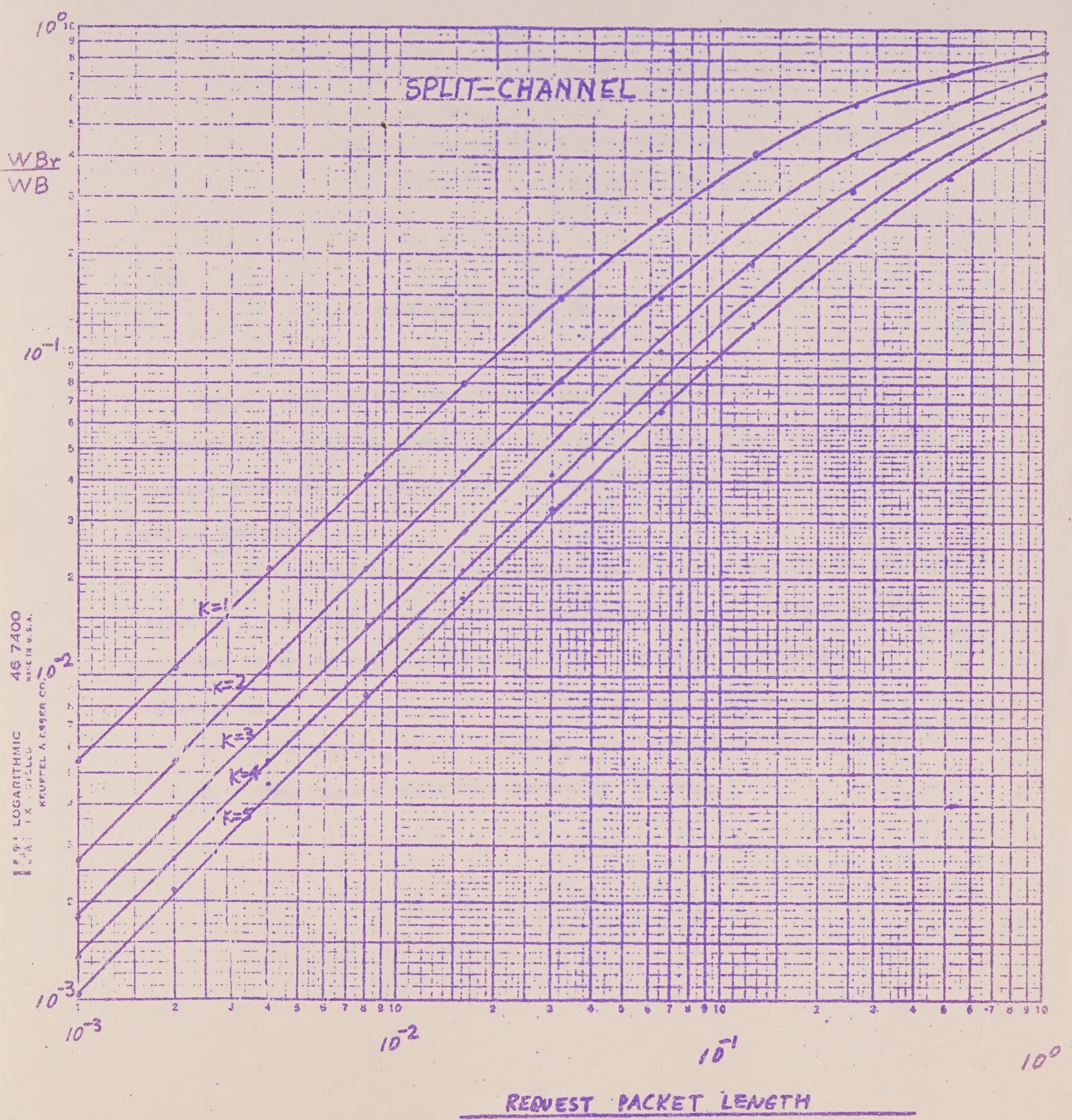
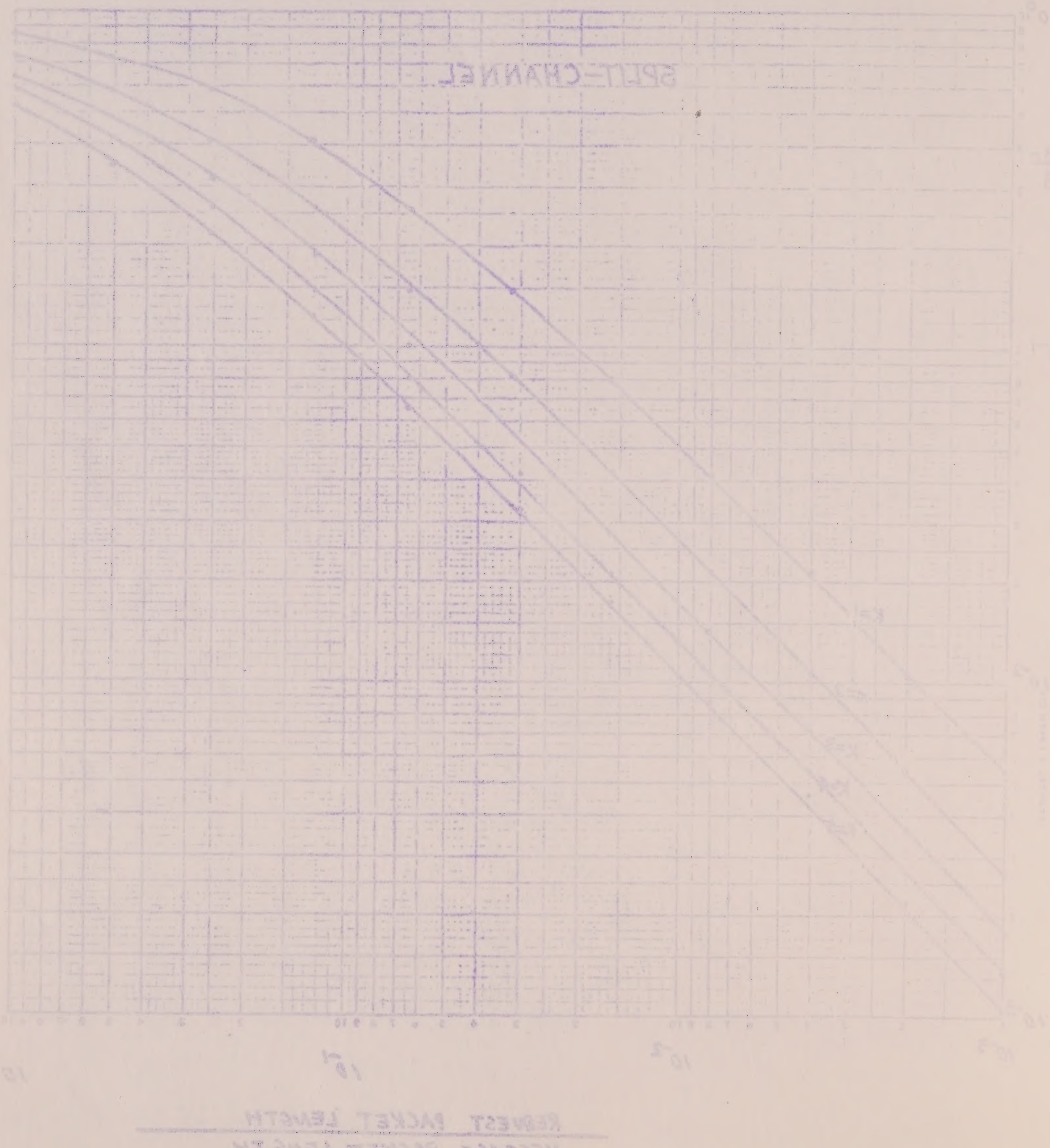
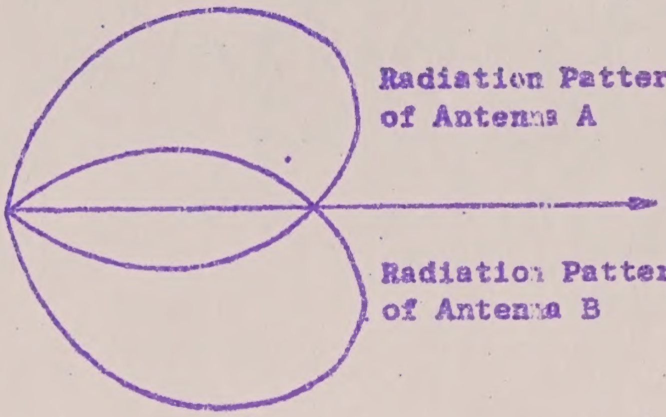

SPLIT-CHANNEL
WBr / WB
K=1
K=2
K=3
K=4
K=5
10^0
10^-1
10^-2
10^-3
REQUEST PACKET LENGTH / MESSAGE PACKET LENGTH
LOGARITHMIC
46 7400

FIG. 7





Antenna Radiation Pattern

Signals received from the directional antennas A and B are sampled alternatively, the strength of the signals from A and B are compared, the antenna structure is rotated until the equal gain line points towards the mobile terminal.

The distance of the mobile terminal from the relay station can be timed by a precision clock from the time elapsed between sending out the terminal ID by the relay station and the reception of the message.

Disadvantage:

1. More complex, hence expensive, transceivers for the terminal.
2. Need logic circuits for the relay station.